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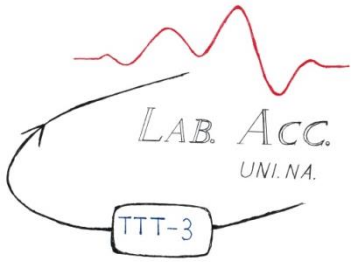
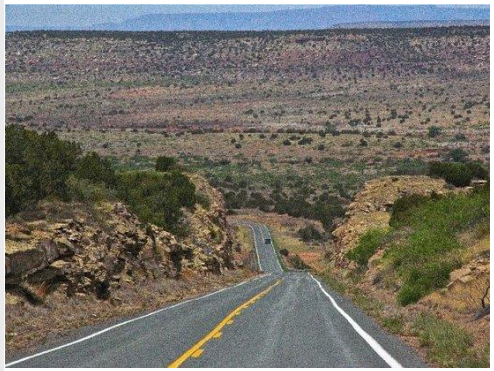


Istituto Nazionale di Fisica Nucleare

Analysis of ^{13}C excited states above the α-threshold by R-matrix analysis of $\alpha+^{9}Be$ elastic and inelastic scattering data

Daniele Dell'Aquila and I. Lombardo

Università degli studi di Napoli "Federico II" & INFN – Sezione di Napoli



dellaquila@na.infn.it

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Clustering in ^{13}C excited states

- Clustering in phenomena in ^{13}C and rotational bands;
- The spectroscopy of ^{13}C above α-threshold;
- Compound-nucleus model and R-matrix calculations;

New data from $\alpha+^{9}Be$ elastic scattering

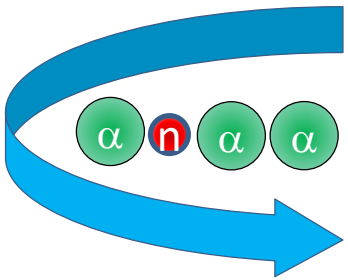
- The Naples experiment: $\alpha+^{9}Be$ resonant elastic backscattering;

R-matrix fit of data

- Preliminary results from elastic (α_0) and inelastic (α_1, α_2) data;
- Possible interpretations;

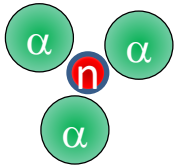
Conclusions and perspectives

dellaquila@na.infn.it



rotating deformed structures → rotational bands.

prolate (nuclear chain structure)



oblate (possible 3α+n Hoyle analog state in 13C)

Near and above the α-threshold →different α-cluster configurations proposed for ^{13}C →theoretical works:

M. Milin and W. Von Oertzen EPJ A **14** (2002) 295
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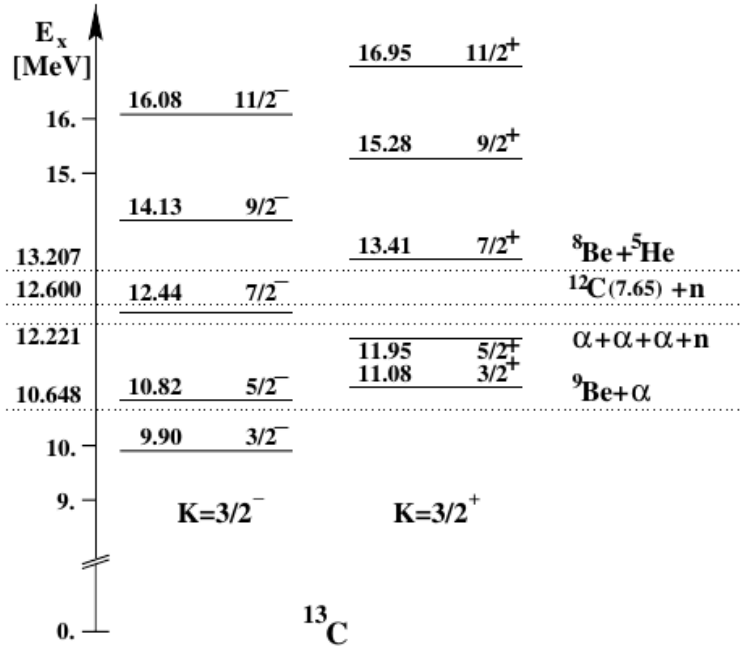

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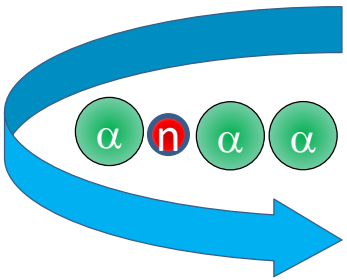

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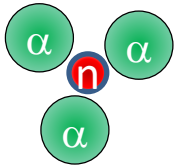

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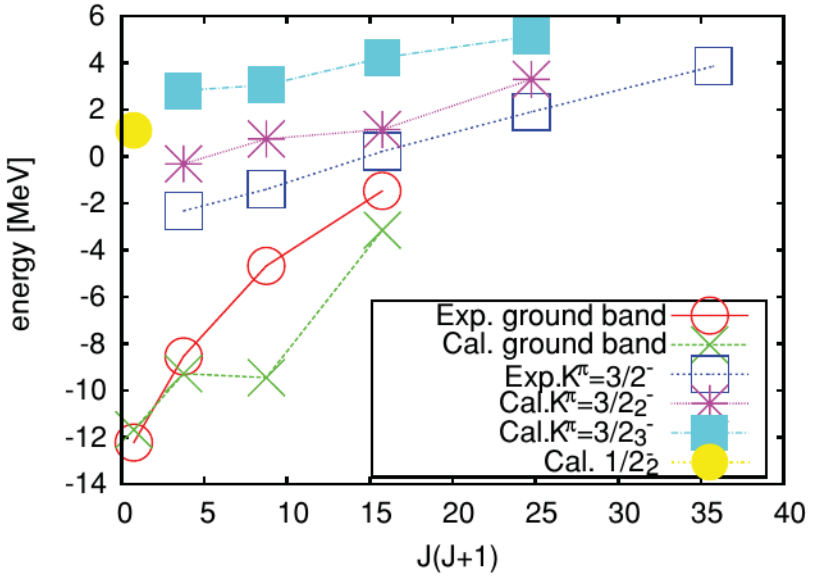

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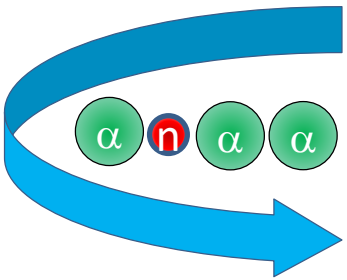

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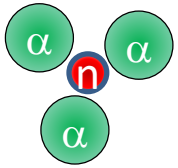

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$1/2^{+}_{5}$ state predicted at 14.9 MeV with a strong $^{12}C(0^{+}_{2})$ + n spectroscopic factor → analog of Hoyle state in ^{13}C.

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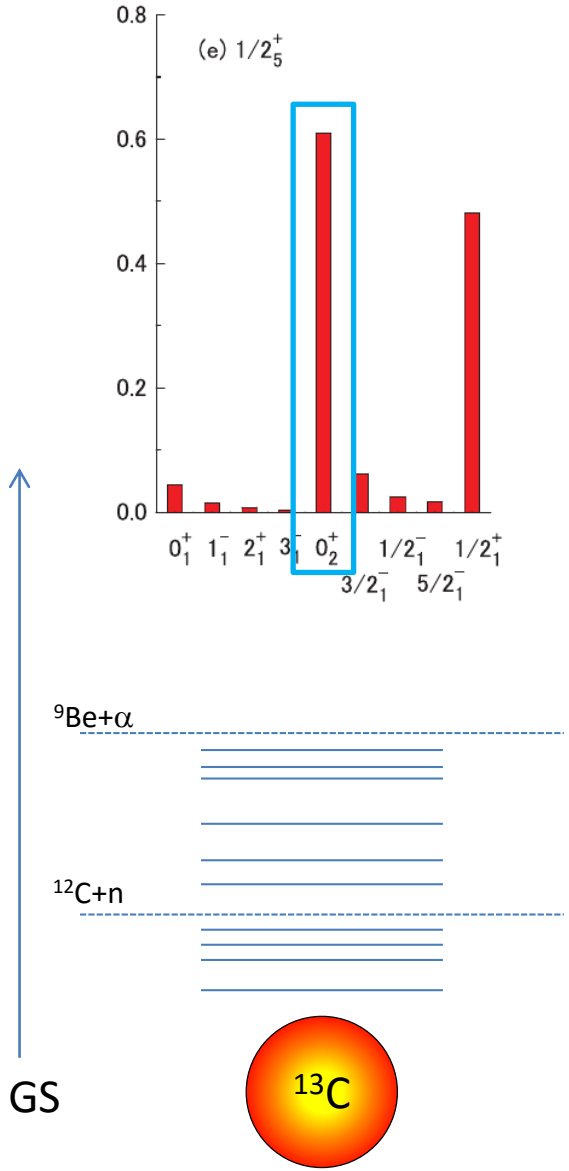

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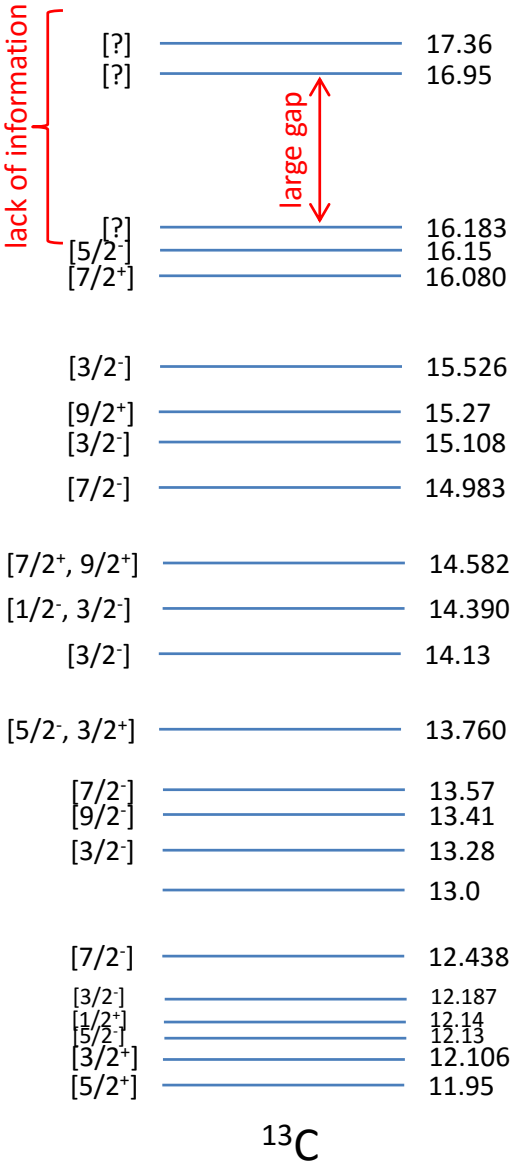
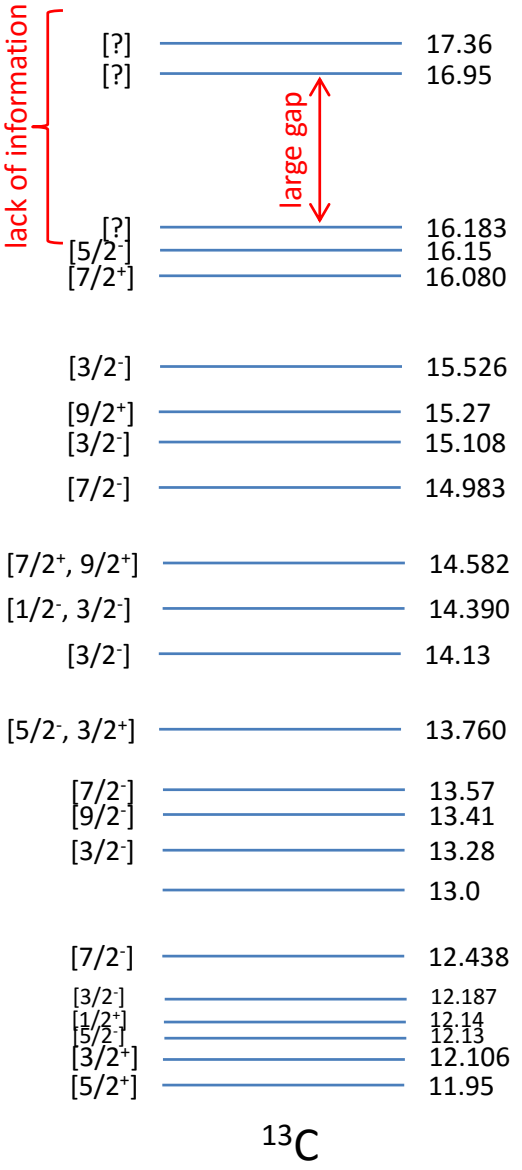


from Ajzemberg-Selove compilation



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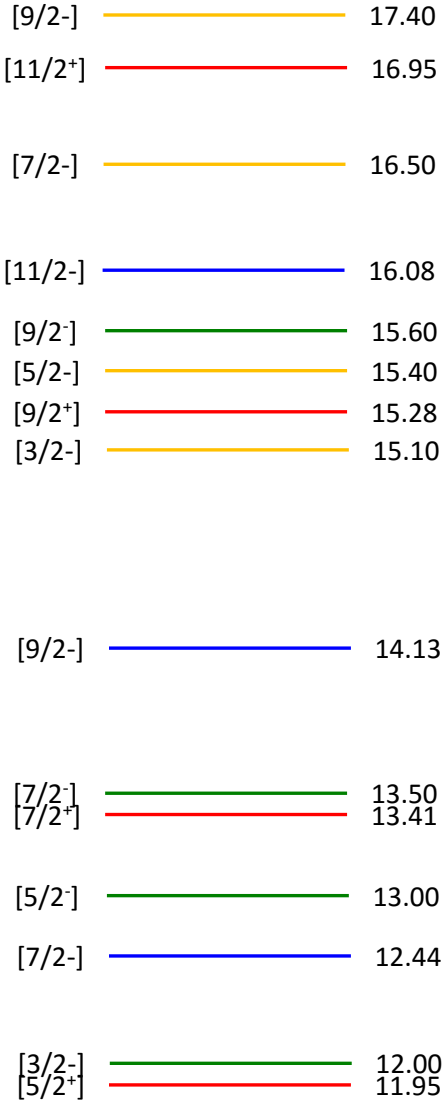


predicted rotational bands

Yamada and Funaki $1/2^+_5$

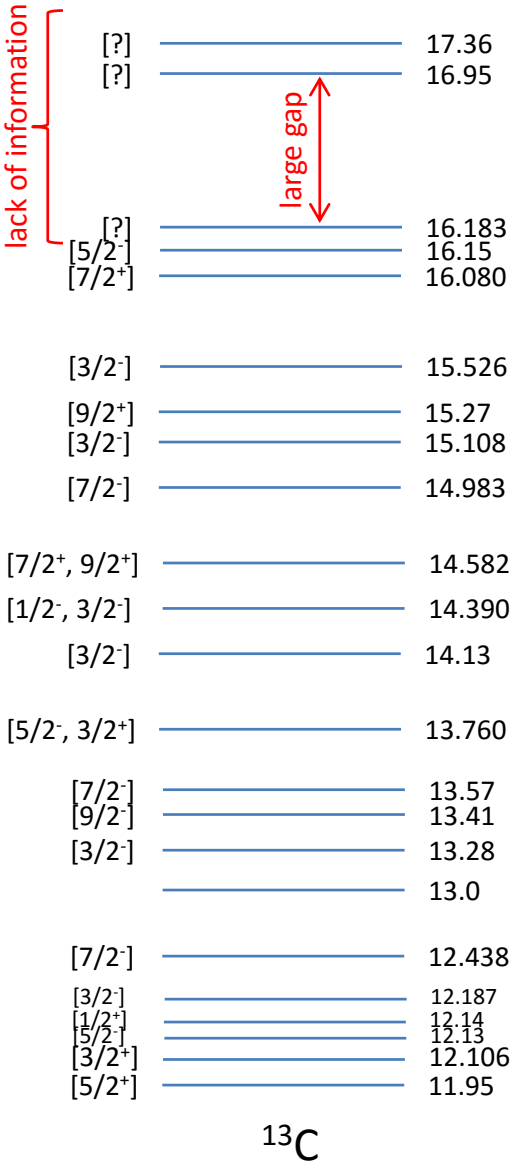
[1/2+] 14.90

Furutachi and Kimunra $K^\pi=3/2^-_3$

Furutachi and Kimunra $K^\pi=3/2^-_2$

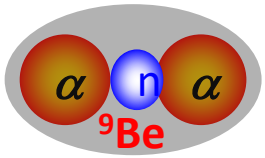
Milin and Von Oertzen $K^\pi=3/2^+$

Milin and Von Oertzen $K^\pi=3/2^-$



from Ajzemberg-Selove compilation

To investigate the structure of ^{13}C above the α-threshold (10.651 MeV) → ^{9}Be(α,n), ^{9}Be(^{6}Li,d),^{13}C(α,α'), ^{9}Be(α,α) etc.



The Resonant Elastic Scattering is particularly suited for investigating states in the compound ^{13}C with α-cluster nature since the ^{9}Be presents a well developed molecular nature.

• R.B. Taylor et al, NPA 65 (1965) 318	DK	$6.3 < E_{lab} < 19.7$
• J.D. Goss et al, PRC 7 (1973)	DK	$1.7 < E_{lab} < 5.6$
• Z.A. Saleh et al, Ann. Phys. 7 (1974) 76	DK	$1.4 < E_{lab} < 2.5$
• J. Leavitt et al, NIM B 85 (1994) 37	DK	$0.6 < E_{lab} < 4.2$
• J. Liu et al, NIM B 108 (1996) 247	DK	$0.9 < E_{lab} < 5.3$
• M. Zadro et al, NIM B 259 (2007) 836	IK	$2.0 < E_{cm} < 4.3$
• M. Freer et al, PRC 84 (2011) 034317	IK	$1.6 < E_{cm} < 6.0$
• I. Lombardo et al, NIM B 302 (2013) 19	DK	$2.4 < E_{cm} < 6.4$

$5/2^+$ 11.97 MeV

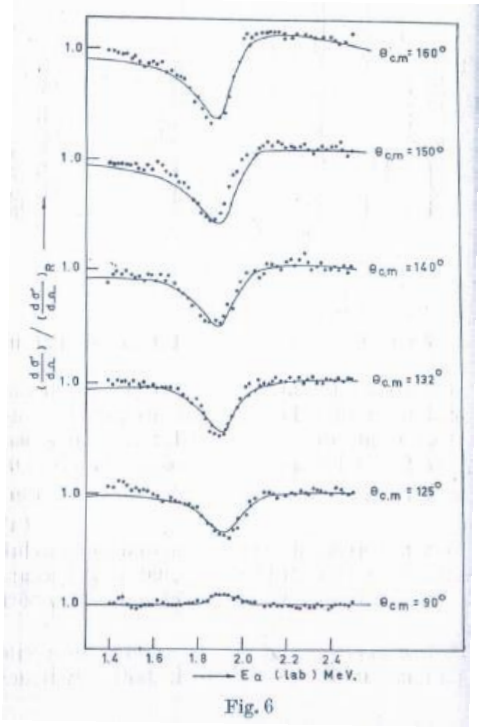
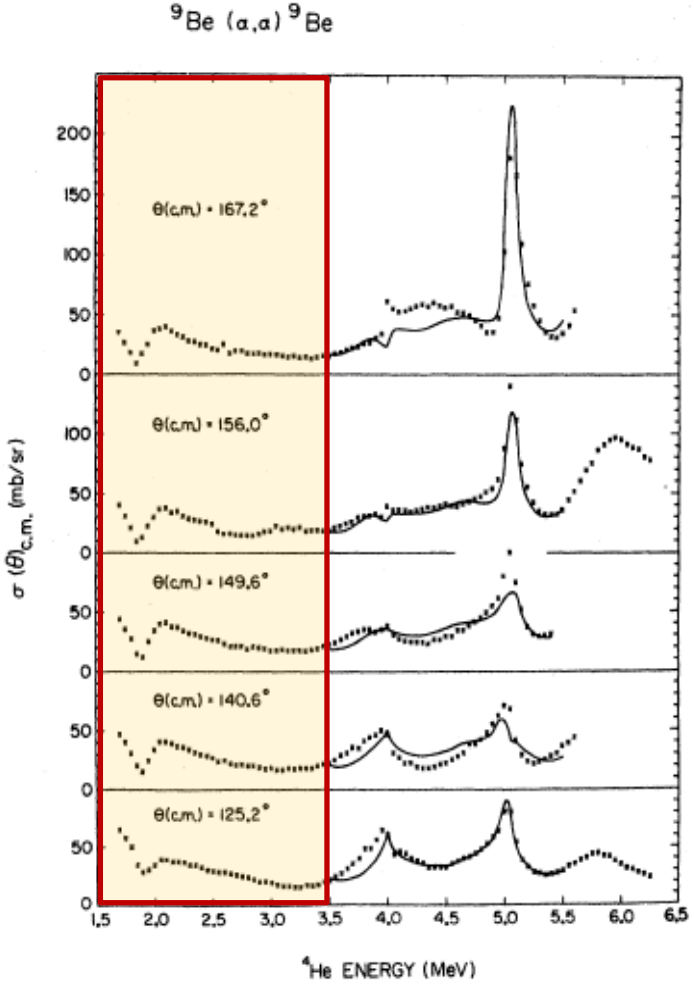
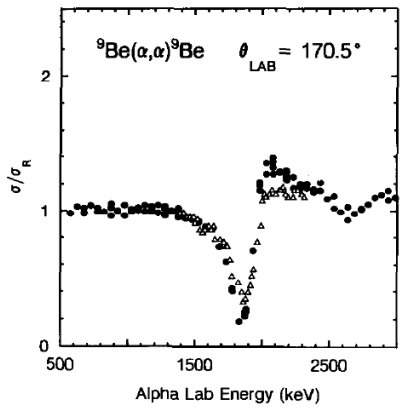


Fig. 6

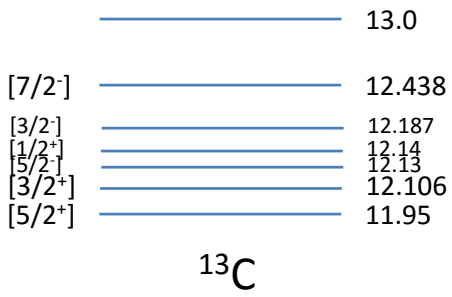
Z.A. Saleh et al., Ann. Phys. (1974)



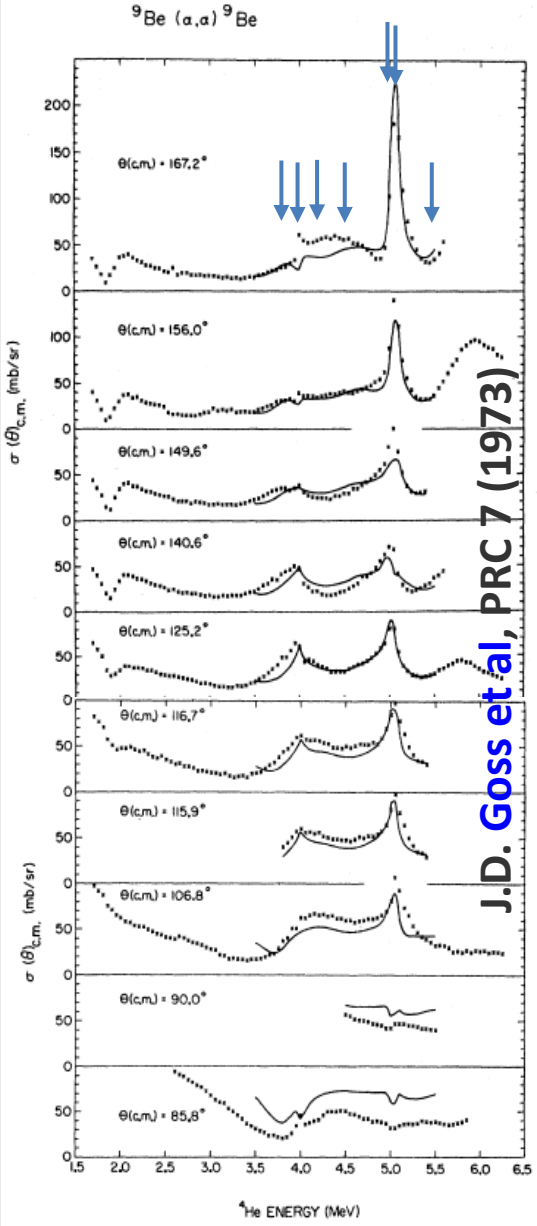
J.D. Goss et al, PRC 7 (1973)



J. Leavitt et al., NIMB (1994)



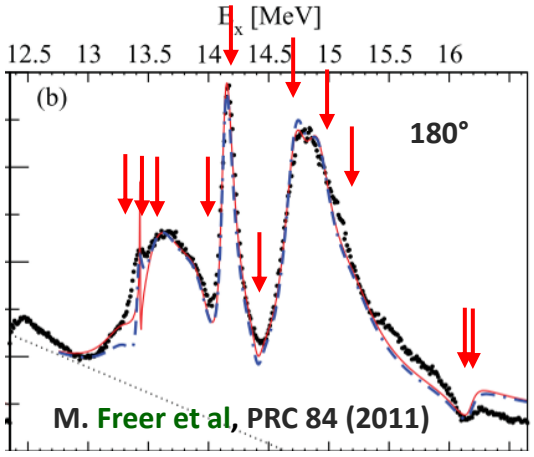
from Ajzemberg-Selove compilation



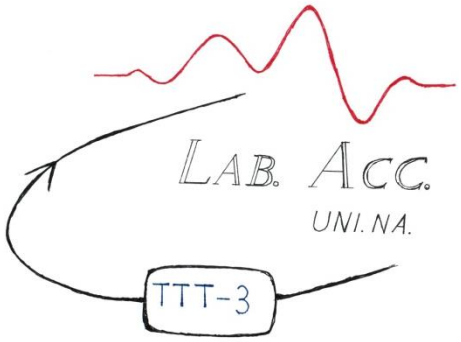
J.D. Goss et al, PRC 7 (1973)

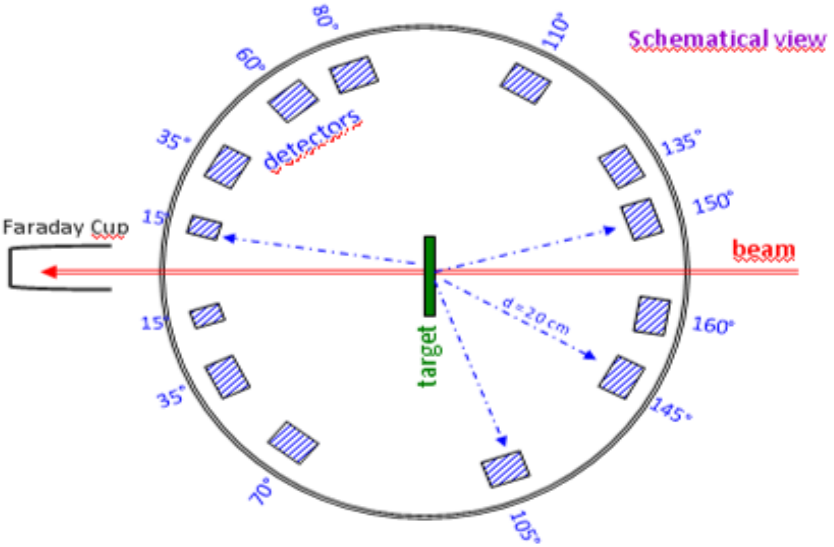
Goss et al. E_x (MeV)	Goss et al. E_α (MeV)	Goss et al. J^π	Goss et al. Γ (keV)	Freer et al. E_x (MeV)	Freer et al. E_α (MeV)	Freer et al. J^π	Freer et al. Γ (keV)	J^π
13.28	3.80	$3/2^-$	343	13.38	3.94	$3/2^-$	340	
13.42	4.00	$(9/2^-)$	58	13.43	4.01	$9/2^-,7/2^+$	2	$7/2^+$
13.56	4.20	$5/2^+$	685	13.53	4.16	$7/2^-$	596	$7/2^-$
13.77	4.51	$3/2^+$	247	13.93	4.74	$5/2^+$	337	
14.11	5.00	$5/2^-$	75	14.13	5.03	$5/2^-$	124	$9/2^-$
14.16	5.07	$7/2^+$	73	---	----	---	---	
14.46	5.50	$(5/2^+)$	400	14.41	5.43	$7/2^-$	111	
---	---	---	---	14.72	5.88	$9/2^+$	285	
---	---	---	---	14.96	6.22	$7/2^-$	406	9/2+
---	---	---	---	15.15	6.50	$5/2^-$	493	$3/2^-$
---	---	---	---	16.14	7.93	$7/2^+$	140	
---	---	---	---	16.16	7.96	$5/2^-$	253	

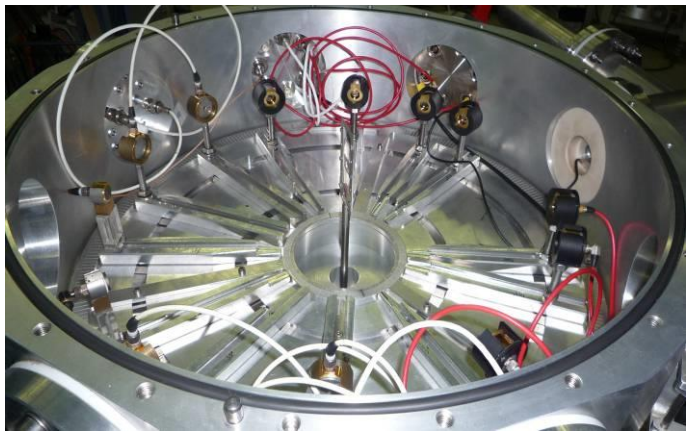
Proposed rotational bands

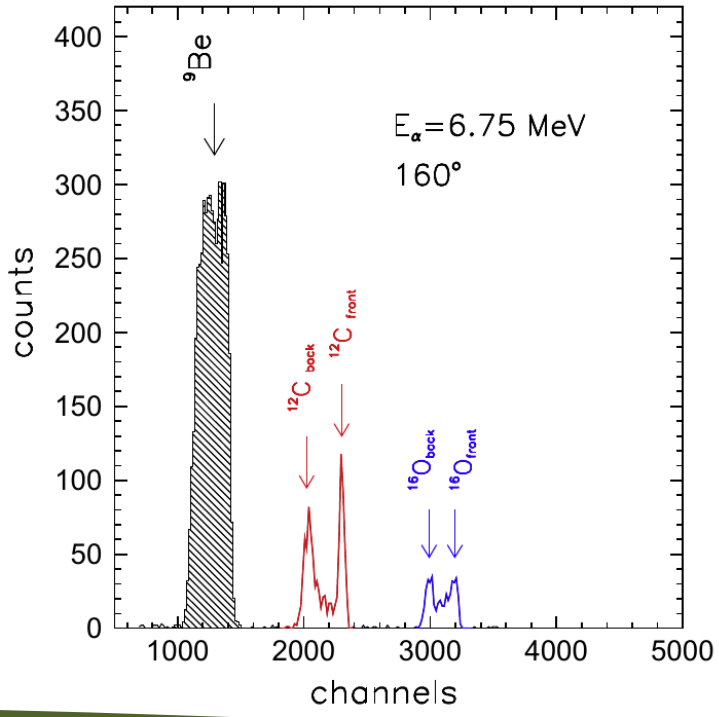


M. Freer et al, PRC 84 (2011)



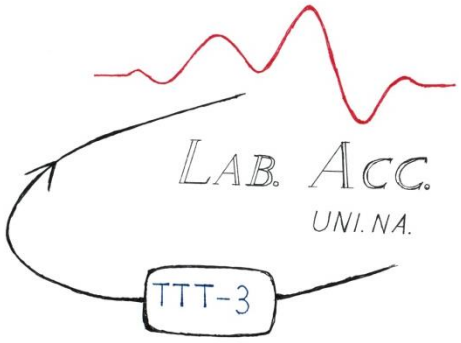






Beam: $^{4}He^{++}$ → E_{Lab}: **3.6 – 10** MeV (**60keV** step, 110 energy changes, energy spread ≤ **3 keV**) TTT-3MV of Laboratorio Acceleratore – Naples, Italy

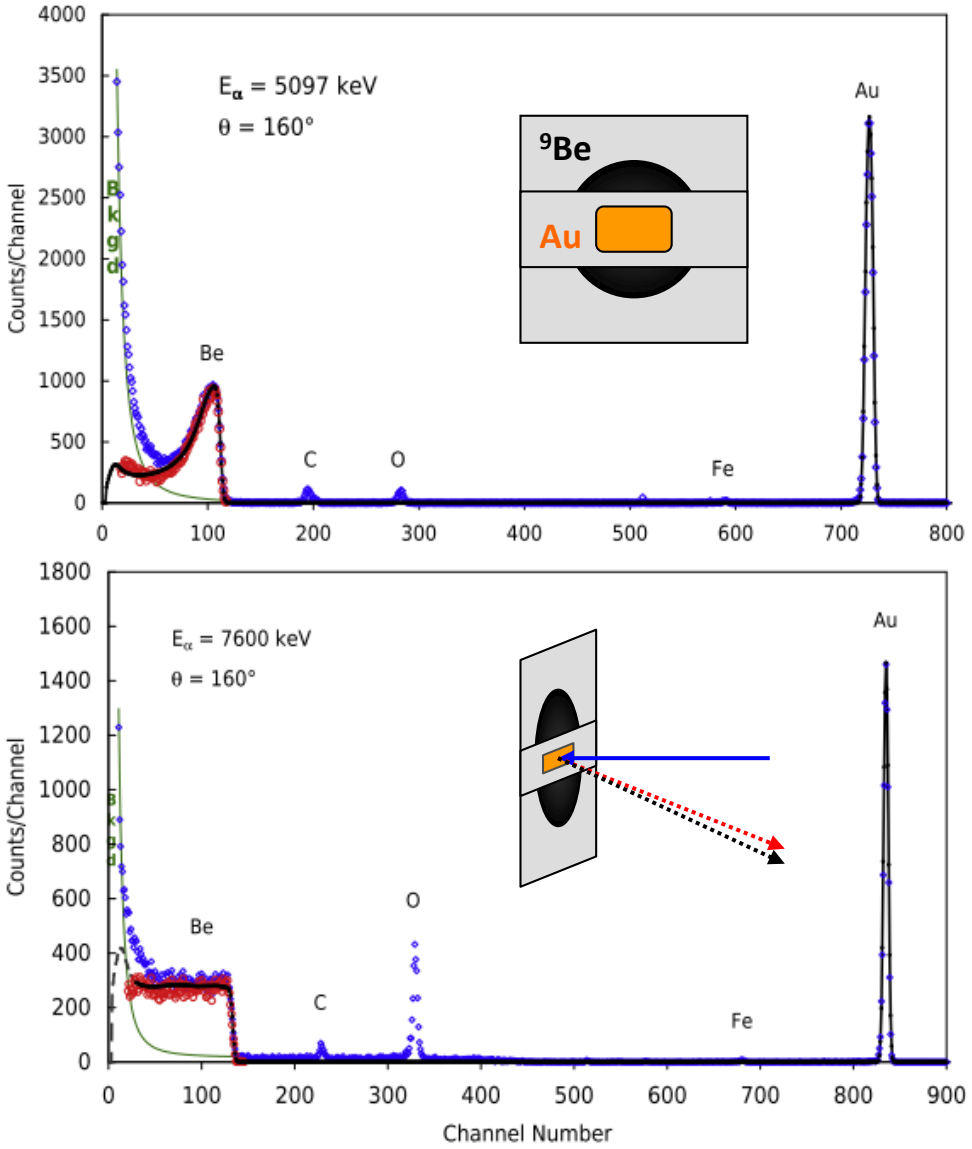
Silicon SB and PIPS detectors: energy resolution **7.0 – 10 ‰**



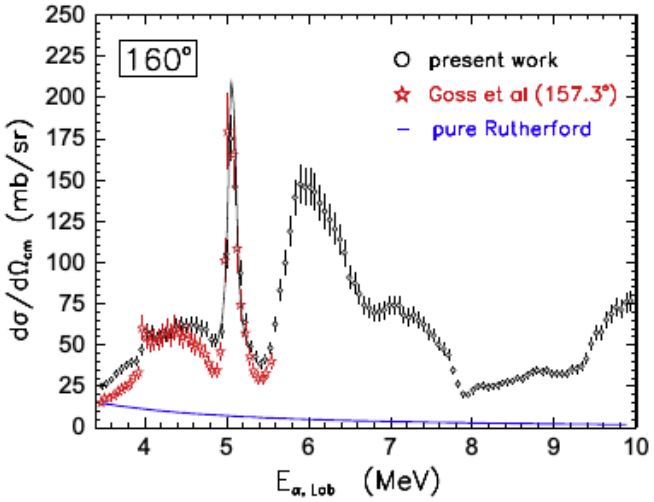
- *background*
- *exp. data*
- *exp. data (background sub)*
- *calculation*

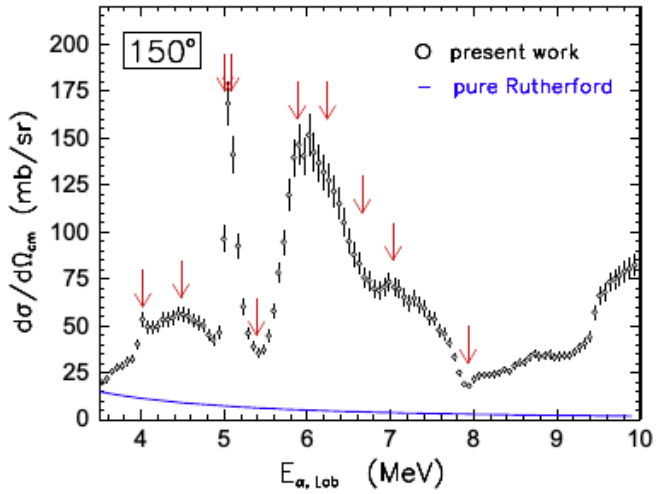
Calculation of thick-target yield including the measured cross section of ^{9}Be(α,α) at 160° → satisfactory agreement with the experimental points (background subtracted) → nice *benchmark* for the cross section.

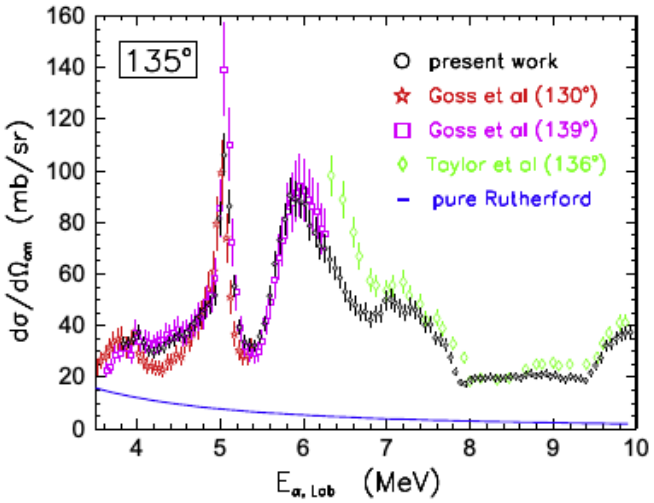
x-section *cross check* with thick target method

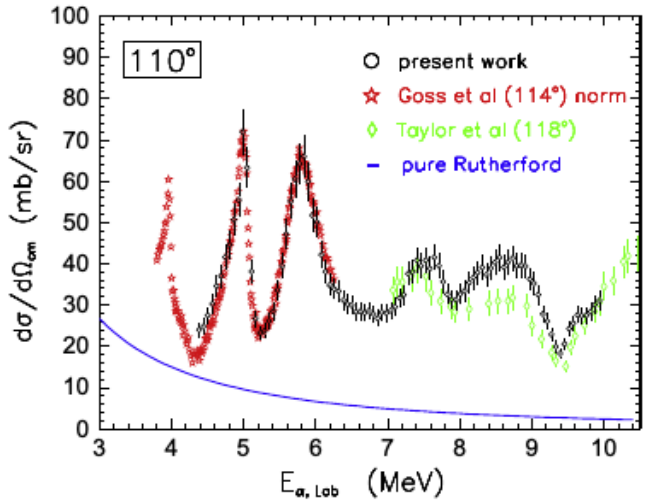


Excitation functions ^{9}Be(α,α) → *resonant structures*









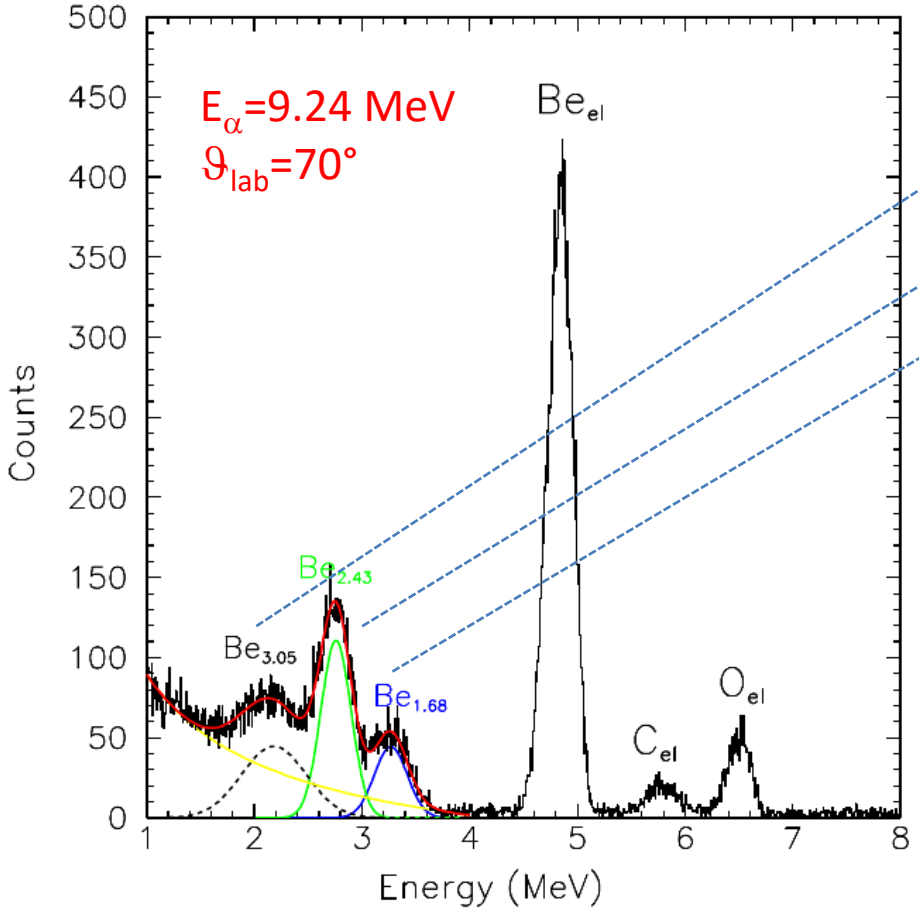
1st point → *check* of our data (excitation function at 160°) with a thick target backscattering experiment .

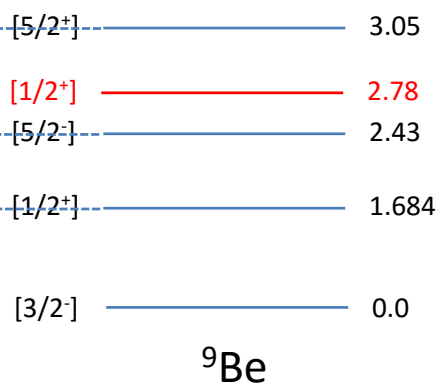
2nd point → check of our data with the literature:

Goss et al PRC 7 (1973) (157.3°, 130° and 114°) → *match* of *shapes* and *absolute values*

Taylor et al NPA (1965) (136° and 118°) → *match of shapes and absolute value at higher energies*

Freer et al PRC 84 (2011) (more backward angle, 180°) → *match* of the *shape.*





Identification of the α_1 and α_2 groups by means of a *multi-parametric fit* → continuus background (*exponential*) to reproduce the data.

State at 2.78 MeV (broad) not included in the fit → never observed in inelastic scattering reactions.

Vanishing contribution of α particles from ^{9}Be break-up → Monte Carlo calculation.

AZURE R-Matrix Program

AZURE2

Comprehensive R-matrix fit of $^{9}Be(\alpha,\alpha_0)$ data (ϑ_{lab}=160°, 150°, 135° and 110°) and $^{9}Be(\alpha,\alpha_{1,2})$ data (ϑ_{lab}=70°) → AZURE2 program. Inclusion of *Goss et al*. data at low energies (157.3°, green triangles).

Channels used to reproduce the data:

1. $^{9}Be(\alpha,\alpha)$
2. $^{9}Be(\alpha,\alpha_1)$
3. $^{9}Be(\alpha,\alpha_2)$
4. $^{9}Be(\alpha,n)$

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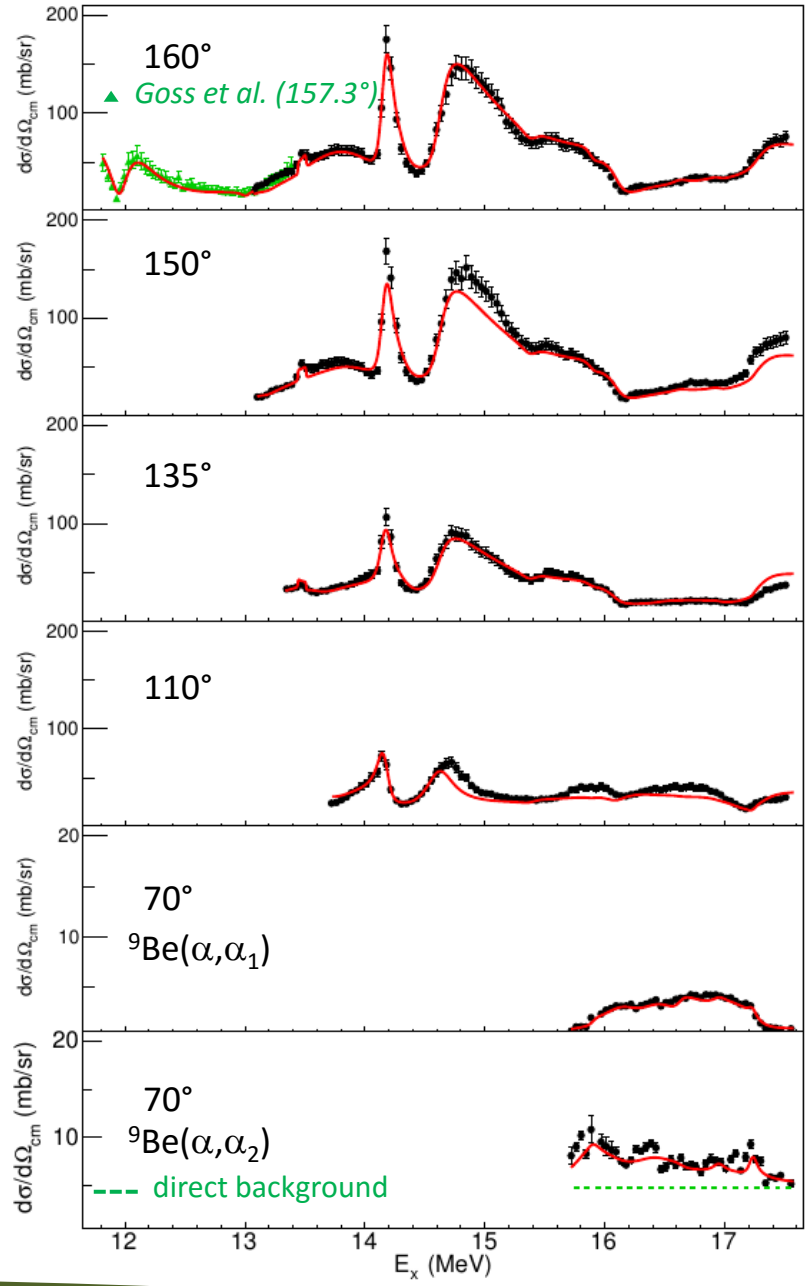
AZURE R-Matrix Program

AZURE2

Comprehensive R-matrix fit of ^{9}Be(α,α_0) data (ϑ_{lab}=160°, 150°, 135° and 110°) and ^{9}Be($\alpha,\alpha_{1,2}$) data (ϑ_{lab}=70°) → AZURE2 program. Inclusion of *Goss et al*. data at low energies (157.3°, green triangles).

E_x (MeV)	J^π	Γ (keV)	Γ_α (keV)	Γ_n (keV)
11.97	5/2+	186	76	110
12.22	5/2-	579	150	429
12.47	1/2-	581	81	500
13.01	1/2+	83	15	68
13.15	3/2-	206	27	178
13.44	7/2+	6	6	0
13.55	7/2-	465	263	203
13.77	3/2-	582	452	129
14.14	5/2-	81	81	0
14.34	7/2-	312	96	216
14.50	7/2+	1622	680	942
14.65	7/2-	339	325	15
14.97	5/2+	1260	1038	222
15.36	3/2+	152	21	131
15.88	7/2-	233	155	23
15.91	5/2-	524	232	30
16.08	3/2+	181	61	116
16.12	1/2-	587	314	130
16.17	5/2+	361	215	121
16.41	5/2-	287	112	28
16.53	7/2+	748	63	245
16.63	3/2-	1184	304	299
16.77	7/2+	1179	240	877
16.94	5/2+	125	10	0
17.16	7/2-	868	506	360
17.21	3/2+	68	28	0
17.28	3/2-	438	335	73

preliminary analysis!!!



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Ajzemberg-Selove			Goss et al.			Freer et al.			Our Data		
E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)
11.95	5/2+	500 ± 80							11.970	5/2+	186
12.106	3/2+	540 ± 70									
12.13	5/2-	80 ± 30									
12.14	1/2-	430 ± 0									
12.18	3/2-	150 ± 40							12.220	5/2-	579
12.43	7/2-	140 ± 30							12.470	1/2-	581
									13.010	1/2+	83
13.28	(3/2-)	340	13.28	3/2-	343	13.38	3/2-	340	13.150	3/2-	206
13.41	(9/2-)	35	13.42	(9/2-)	58	13.43	9/2-,7/2+	2	13.454	7/2+	6
13.57	7/2-	620	13.56	5/2+	685	13.53	7/2-	596	13.553	7/2-	465
13.76	(5/2,3/2)+	≈ 300	13.77	3/2+	247	13.93	5/2+	337	13.768	3/2-	582
14.13	3/2-	≈ 150	14.11	5/2-	75	14.13	5/2-	124	14.135	5/2-	81
			14.16	7/2+	73						
14.39	(1/2,5/2)-	280 ± 70	14.46	5/2+	400	14.41	7/2-	111	14.342	7/2-	312
									14.500	7/2+	1622
14.58	(7/2+,9/2+)	230 ± 60				14.72	9/2+	285	14.650	7/2-	339
14.98	(7/2-)	380 ± 60				14.96	7/2-	406	14.970	5/2+	1260
15.10(8)	3/2-	5.5									
15.27	9/2+					15.15	5/2-	493	15.357	3/2+	152
15.53	(3/2-)	150 ± 30							15.876	7/2-	233
									15.906	5/2-	524
16.08	(7/2+)	150 ± 15				16.14	7/2+	140	16.084	3/2+	181
16.15	(5/2-)	270				16.16	5/2-	253	16.121	1/2-	587
16.18		(40 ± 20)							16.173	5/2+	361
									16.413	5/2-	287
									16.533	7/2+	748
									16.628	3/2-	1184
									16.770	7/2+	1179
16.95		330							16.937	5/2+	125
									17.157	7/2-	868
									17.209	3/2+	68
									17.277	3/2-	438
17.36		190									
17.53		17 ± 6									
17.69	(3/2,5/2)	170									

• Investigations of ^{13}C spectroscopy at E_x larger than the *α emission threshold* → useful method to unveil *cluster structures* in *non self-conjugated nuclei*

• A possible reaction → $^{9}Be(\alpha,\alpha)$ RES→ *few data* available in the literature (many uncertainties in J^{π} assignments)

• A new experiment carried out at Laboratorio dell'Acceleratore (TTT-3MV) of the University of Naples "Federico II" → direct kinematics → excitation functions of $^{9}Be(\alpha,\alpha_0)$ EBS at ϑ_{lab} = 110°, 135°, 150°, 160°in E_α = 3.6 – 10 MeV energy range → inelastic α_1 and α_2 at ϑ_{lab} = 70°

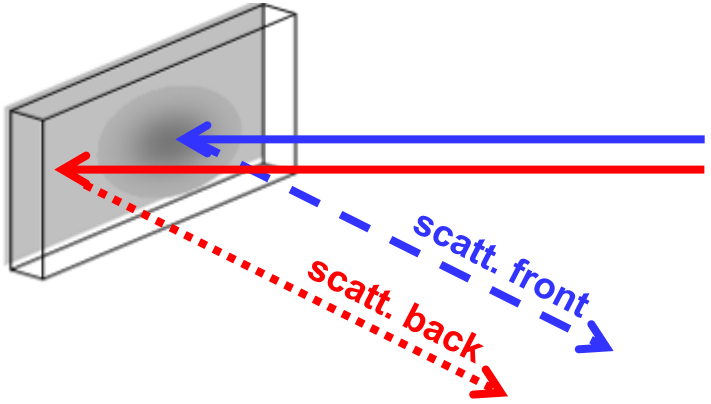
• Comprehensive *R-matrix fit* of the data by including the $^{9}Be(\alpha,\alpha_0)$ data (160°, 150°, 135° and 110°), the $^{9}Be(\alpha,\alpha_{1,2})$ data (70°) and the low energy points from *Goss et al*.

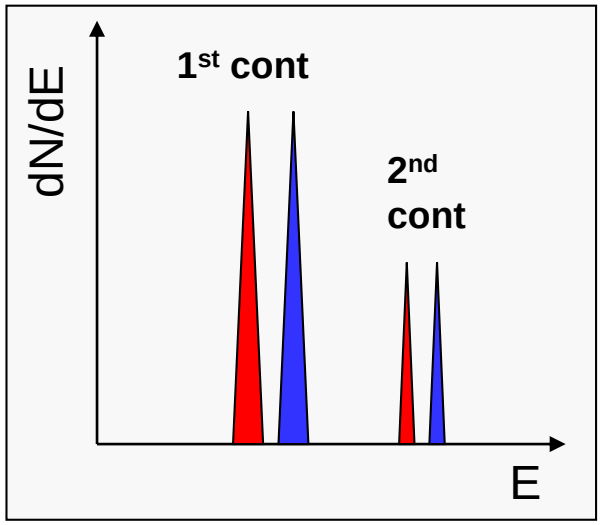
• Strong efforts to fit data at various angles → reproduction of data with a reasonable set of parameters in a wide energy range → new *preliminary spectroscopic information* in the region E_x = 16 MeV – 17 MeV

• New data with different techniques and channels would help in the understanding of ^{13}C spectroscopy in this complicated region.

Thank you for your attention.

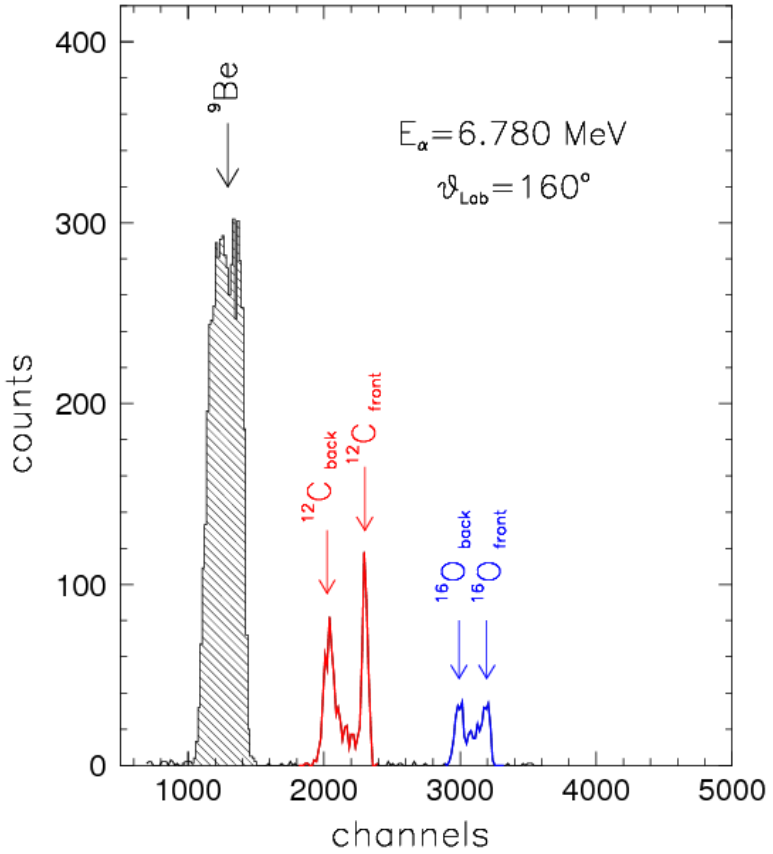
Further Slides





Target ^{9}Be → 129 μg/cm²
Formvar → 6 μg/cm²
Build-up (other experiments)

Manufactured by INFN
Laboratori Nazionali del Sud - Catania



- good *identification* of *scattering* events
→ *kinematics* and *target structure*
- very *low background*